

TABLE 2.—*In the Great Plains States north of Oklahoma, where there are usually periods of considerable length in the wintertime when grazing is not possible.*

Annual precipitation:	Cattle per square mile.
10 to 15 inches.....	19
15 to 20 inches.....	38
20 to 25 inches.....	76
25 to 30 inches.....	265
30 to 40 inches.....	409

TABLE 3.—*In the central and upper Rocky Mountain and Pacific States, mostly summer ranges, the period of grazing, varying from 3 to 7 months, depending upon the location.*

Annual precipitation:	Cattle per square mile.
5 to 10 inches.....	20
10 to 15 inches.....	28
15 to 20 inches.....	47
20 to 25 inches.....	63
25 to 30 inches.....	97

The greater grazing capacity with the lighter rainfall amounts in the first part of Table 3, as compared with Table 2, is undoubtedly explained by the shorter grazing period in the Rocky Mountain States. On the other hand, the smaller capacity with the heavier rainfalls in the last part of Table 3 as compared with Table 2 seems to be because the regions of heaviest rainfall in the Rocky Mountain States are at the highest elevations where the country is very rough and the available grazing areas small as compared with the Great Plains territory.

The ratio between the number of sheep that can be grazed as compared to cattle as given by different men

varied between 14 and 2 to 1. The average is 7 sheep to 1 head of cattle, and this is the ratio that was used in changing the number of sheep grazed into terms of cattle.

In the following table all of the available data from the Great Plains westward are averaged together after correcting for the period of grazing. That is, if the grazing period is only 6 months, the grazing capacity as reported is divided by 2. If it is only 4 months, the capacity figures are divided by 3.

TABLE 4.—*Relation between the annual precipitation and the grazing capacity of ranges from the Great Plains westward (not including California).*

Annual precipitation:	Cattle grazed per square mile.
0 to 5 inches.....	0
5 to 10 inches.....	8
10 to 15 inches.....	14
15 to 20 inches.....	20
20 to 25 inches.....	43
25 to 30 inches.....	66
Over 30 inches.....	138

While Table 4 may represent the theoretical grazing capacity of ranges for all-the-year grazing, it is not so reliable as the preceding tables, which show averages for the actual grazing that is taking place under different rainfall amounts and for such periods as the season will allow.

The author wishes to give due credit for valuable data furnished by the field officials of the Weather Bureau and the Forest Service.

NEW AEROLOGICAL APPARATUS.¹

By S. P. FERGUSON, Meteorologist.

[Weather Bureau, Washington, D. C., July, 1920.]

SYNOPSIS.

The height to which a balloon will rise depends primarily upon the ratio of the lift to the weight carried. The large rubber balloons of either the Assmann or Paturel type required to lift the meteorographs heretofore employed in aerological investigations are costly, and doubtless this circumstance has limited the use of balloons-sondes. An investigation of the methods and requirements of aerology has led to the production of a new meteorograph of very simple construction, important parts of which can be made economically in quantity. The scales, particularly that of the pressure-element, are wider than those of other instruments of the kind, the various operations of preparation and reading the records have been simplified, and the weight is less than one-third that of the next lightest instrument that has been used with balloons-sondes.

One or two small pilot balloons, costing but one-tenth as much as the Assmann balloons, can lift the new meteorograph, and since the pilot balloons are of better quality the heights attained should be greater than those now possible with the larger balloons and heavy equipment.

An experimental engraving meteorograph and a temperature-element without pivots, suitable for use with the Goddard rocket or in other apparatus are described in order to suggest the direction of further study and experiment.

INTRODUCTORY.

The maximum height attainable by a balloon depends primarily upon the relative density of the gas in the balloon and that of the air, the ratio of the weight to the total lift at the ground, leakage, differences of temperature, and the material of which the balloon is composed. The maximum height, or "ceiling", of a balloon of rigid materials (silk, paper, goldbeater's skin, etc.) may be determined approximately by the degree of inflation required to raise it from the ground. If it will rise when one-half, one-fourth, or one-eighth

full, and so on, the maximum height will be where the atmosphere is one-half, one-fourth, or one-eighth, etc., as dense as it is at the ground. Obviously, even if it is made of very light material, such a balloon must be very large if great heights are desired; and during the first campaign with balloons-sondes, the French experimenters, considering all circumstances, placed the practical limit of the method at 30,000 meters, if a balloon whose capacity was 5,000 cubic meters were used. Up to 1902 the capacity of the paper and silk balloons used by Teisserenc deBort and Assmann was about 500 cubic meters, the excess lift about 140 kilograms, and the average and maximum heights attained, about 8,000 and 18,000 meters, respectively.

The Assmann expanding balloon, introduced in 1902, revolutionized aerological exploration, for, with a sealed rubber balloon containing but 6 cubic meters of hydrogen, the average height attained has been between 12,000 and 15,000 meters and the maximum 35,000, or almost twice the heights previously accomplished by rigid balloons. The highest ascension in the United States, by Mr. Sherry, then of the Weather Bureau, is particularly noteworthy for the reason that trigonometric observations of altitude were made at two stations up to the highest point reached (32,000 meters).

The most important advance in the direction of economical experimenting has been made by Mr. W. H. Dines, whose baro-thermograph weighs but 48 grams and can be lifted by a small pilot balloon. Time is not recorded by this instrument and progressive changes of condition must be determined from frequent ascensions.

The heights attained by the Assmann balloons have been very variable, chiefly because of the variable

¹ Presented in large part before the American Meteorological Society, Washington, D. C., April 22, 1920.

quality of the sheet rubber of which they are made. The moulded balloons supplied by Paturel and others are much better, but the efforts of Fassig in 1906, and others since that time, to secure balloons of this kind large enough to lift the meteorographs usually employed, have not been successful, probably for the reason that the moulding process is economical only in the production of small balloons in large quantities.

After the completion of the first exploration with *ballons-sondes* in this country, in 1907, the writer made a few tests of, Paturel balloons and some experimental devices with the object of developing, if possible, recording apparatus suitable for use with small balloons. These experiments indicated the probability of success by the use of apparatus based upon a special kite-meteorograph, designed in 1905, the weight of which was but two-thirds that of other instruments having the same range and capacity. Opportunity to make use of this new design did not come until 1919, when it was submitted to the committee of the Weather Bureau investigating the Goddard exploring rocket, with the suggestion that the possibilities of *ballons-sondes* had not been exhausted.

The first instruments of this new pattern were received in December, 1919. As yet, no ascensions have been attempted, but tests in the laboratory indicate that requirements have been met very satisfactorily.

Comparison of balloons and meteorographs.

ASSMANN BALLOONS.

	No. 1.	No. 3.	No. 5.
Diameter:			
Full.....	1.20 meters	1.50 meters	2.00 meters
Distended.....	1.35 meters	1.75 meters	2.25 meters
Weight.....	1.36 kilograms	1.50 kilograms	3.23 kilograms
Capacity:			
Full.....	1.00 cubic meter	2.00 cubic meters	4.00 cubic meters
Distended.....	1.50 cubic meters	3.00 cubic meters	6.00 cubic meters
Lift:			
When full.....	1.00 kilogram	2.00 kilograms	4.00 kilograms
When distended.....	1.50 kilograms	3.00 kilograms	6.00 kilograms
Cost (1910).....	\$12.00	\$17.00	\$36.00

BALLOONS OF THE PATUREL TYPE.

Diameter.	Weight.	Diameter at time of rupture.	Lift, when half inflated.	Lift, inflated to point of rupture.	Cost.
	grams	mm.	grams	grams	
165 millimeters *.....	28	930	200	400	\$0.75 (1918).
200 millimeters †.....	34	1,200	600	1,200	1.80 (1908).
220 millimeters †.....	36	1,100	400	800	1.50 (1918).
300 millimeters *.....	43	1,500	1,000	2,000	2.00 (1918).

* Made in the United States, 1918.

† Made by Paturel, Paris, France, 1908.

METEOROGRAPHS AND ACCESSORIES.

Meteorograph.	Weight of—			Total weight.	Hydrogen required.	Cost, instrument only.	Cost of accessories.
	Instrument.	Parachute.	Basket.				
	grams	grams	grams	grams	m ³		
Bosch (Germany, 1904)....	600	500	500	1,700	2.5	\$100.00 *	\$10.00 *
deBort (France, 1904)....	400	425	113	938	1.5	55.00 *	7.50 *
Fergusson (U. S. A., 1919)†.	180	50	45	275	1.0	100.00 †	3.50 †

* In Europe, 1904-1910.

† In America, 1919.

The quantity of hydrogen stated is that necessary to give an excess or surplus lift of 500 to 1,000 grams. When the Bosch instrument is employed this excess is

obtained only when the largest Assmann balloons are used. For the deBort meteorograph, the No. 3 Assmann balloon usually is sufficient and very probably two 300-millimeter Paturel balloons would be satisfactory, although possibly the rate of ascension would be slower than with a larger balloon. The important result shown by these comparisons is that aerological exploration with small, light apparatus is far less costly than when heavy instruments of older patterns are employed; also, if the market values of the instruments are corrected to the same year it will be seen that the new instrument is the least costly of the three.

DESCRIPTION OF THE NEW METEOROGRAPH.

Practically all meteorographs that have been used with *ballons-sondes* are simple modifications of well-known baro-thermo-hygrographs. Experience, and the analysis already referred to, of the methods of aerology, indicated a need of improvement in the following particulars:

(1) Instruments generally used are unnecessarily complex, most parts are handmade and not adapted to production in quantity, and repairs ordinarily can not be made except by a skilled instrument maker.

(2) Rigidity, or resistance to flexure, of supports, usually secured by the use of thick base plates and braces attached to pivot supports, is not permanent.

(3) The ordinary commercial clocks used run 30 to 40 hours with one winding. The time-drum rotates once in one hour, and since an ascension seldom occupies more than three hours, portions of the record are frequently obscured or lost because of tracings of surface conditions superimposed after the instrument reaches ground and before the clock stops. Several devices have been employed to remove the markers from contact with the record sheet or stop the clock, etc., but all these add to the cost of the instrument and increase the number of operations to be performed at the time of an ascension. Instances have occurred of loss of records due to failure to set such devices.

(4) The number of operations required when the instrument is prepared for an ascension and in measuring and reading the records is unnecessarily large.

It is believed that in the design of the new meteorograph these defects have been avoided, although further improvement, particularly in rendering the mechanisms more easily accessible is to be desired. The most important deviations from prevailing usage are (1) the use of simple parts that can be produced economically, (2) the use of a system of construction whereby strains tending to cause flexure and disturbance of adjustment are supported by the edges and cylindrical parts of the case and base, (3) the adoption of a single time-arc for all markers, and (4) the use of a two-part scale for the barograph.

The general appearance of the meteorograph and the basket is shown by the two photographs. The cage or basket is composed of three hoops of rattan provided with two crosspieces on which the instrument rests. Light cords attached to metal loops on the case serve to keep the instrument in the center of the cage, where it is easily accessible for adjustment at any time before an ascension. Details of the case, supports, clock, etc., are shown in figures 1 to 12, inclusive, and a schematic record appears in figure 13.

Clock.—The clock, usually the heaviest single part of a light recording instrument, received attention first. The movement employed, which was selected from a number of the simpler American clocks, is of the same general

character as the well-known Ingersoll watch, but is stronger and the teeth of the pinions are cut. The quality is, perhaps, more variable than is desirable, but the movement is a good timekeeper and so cheap that it is economical to use even if the number of rejections is large.

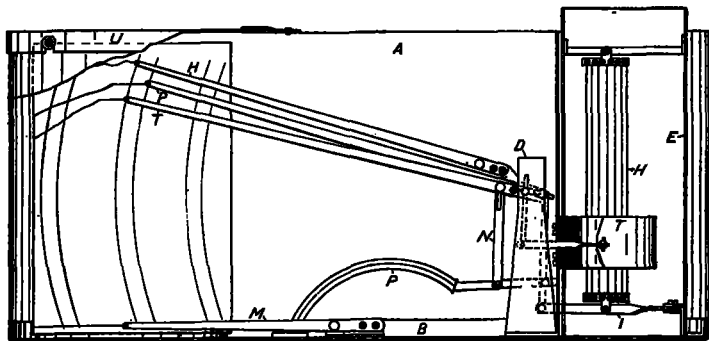


FIG. 1

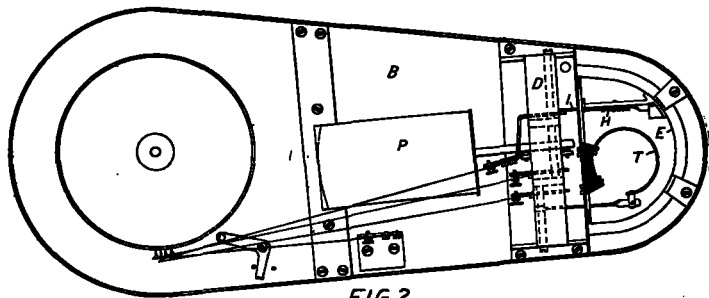


FIG. 2

It has been found satisfactory in kite-meteorographs. As shown in figures 3 and 4, the heavy spring and gear usually employed to drive the clock for 30 hours, together with adjacent portions of the plates (indicated by dotted lines), have been removed and a mainspring (S) placed directly on the center staff or minute-hand arbor, to which the time-drum is clamped. At this point a small watch spring is amply powerful and the number of rotations of the drum (ordinarily less than seven) can be limited as desired by winding the spring the required number of turns.

The cylindrical part of the time-drum is of hard sheet aluminium about No. 35 gauge, fitted to heads spun from heavier metal (No. 26 gauge). Cylinders made in this way are much lighter than those cut from tubing and a true cylinder is more easily obtained. The lock seam (C) projects inside, hence does not obstruct the markers. The drum is clamped to the top of the center staff and the bottom flange or head fits smoothly over the adjustable collar (F), just above the clock case (fig. 4). This method of securing the drum admits of unclamping and adjusting for time without disturbing other adjustments; also, the left-hand thread on the center staff admits of winding the mainspring simply by turning the drum backward, after the clamp screw is tight.

Recording mechanisms.—These are of the same general character as similar parts of instruments devised by Richard, Bosch, and others, but much lighter. The Bosch method of adjusting the ranges of the elements is employed.

Temperature-element.—This is a strip of "thermostatic metal," composed of closely-united sheets of invar and bronze, but 0.2 mm. thick, and, with the possible exception of Richard's temperature-element, far more sensitive and more powerful than any formerly employed

in instruments of this kind. The exposure of the temperature-element is shown in figures 1 and 2. The element (T) is secured inside the tube (E) which extends vertically through the case of the meteorograph but is attached only to the base-plate and the upright carrying the recording mechanisms. (T) is insulated from (E) and from the upright so that there is no conduction of heat from the base or cylinder, also, since air can pass freely between the cylinder (E) and the case, the element is not affected by radiation from any part exposed to direct sunshine. The range adopted is 1 mm. to each 2° C.

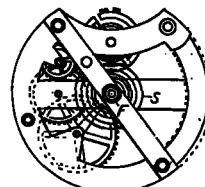


FIG. 3

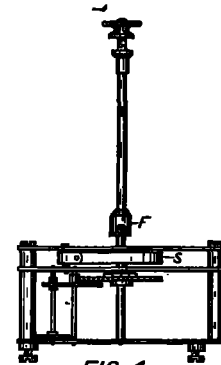


FIG. 4

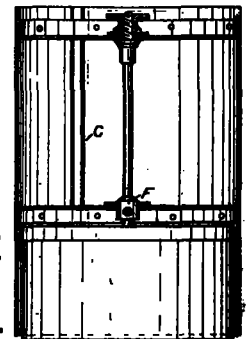


FIG. 5

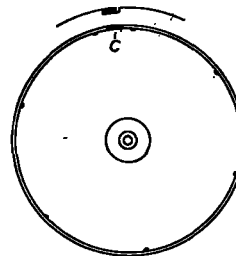


FIG. 6

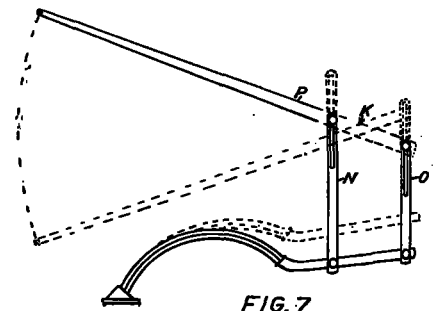
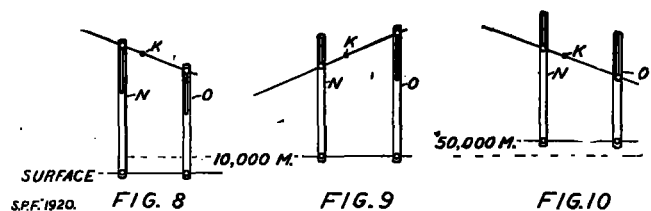


FIG. 7



S.F.F. 1920.

FIG. 8

FIG. 9

FIG. 10

Pressure-element.—When, as in the present instance, the records may extend practically through the entire range of atmospheric pressure, a wide scale is desirable in order that the very small changes at great heights may be recorded and read with reasonable accuracy. An ordinary or usual ratio of the scale of a recording instrument to that of the mercurial barometer is about 1 to 10, i. e., 1 mm. of movement of the pen of a barograph at sea level is equal to a change of pressure of 10 mm. of mercury. As shown in the accompanying table, this scale, at great heights, becomes so contracted that a considerable change of height causes so small a movement of the recording pen that the determination of the height or other circumstances of an important change of condition becomes very uncertain.

Values of the pressure-scale at different heights.

Height.	Pressure.	Difference or change.	Scale of Meteorograph.	
			One-part, (1-10).	Two-part.
	mb.	mb.	mm.	mm.
Sealevel.....	1,013.3			
5 kilometers.....	540.0	473.3	35.5	1-10 { 35.5
10 kilometers.....	224.0	316.0	23.7	1-10 { 23.7
15 kilometers.....	119.9	104.1	7.7	1-10 { 15.4
20 kilometers.....	54.7	65.2	4.8	1-10 { 9.6
30 kilometers.....	11.5	43.2	3.2	1-5 { 6.4
40 kilometers.....	2.2	9.3	0.7	1-5 { 1.4
50 kilometers.....	0.5	1.7	0.1	1-5 { 0.2

Since readings of record-sheets usually can not be depended upon within 0.1 mm. of space traversed, it is apparent that if the ratio 1 to 10 is employed, heights exceeding 30,000 meters may be uncertain to an amount in excess of 2,000 meters. Obviously, with a scale of 1 to 5, the bulk and consequently the weight of the instrument would be prohibitive unless very large balloons could be used; and with the two-part scale indicated in the last column, (in which the portion above 10,000 meters is twice as wide as the portion below,) the instrument still might be too heavy for the small balloons it is intended to use.

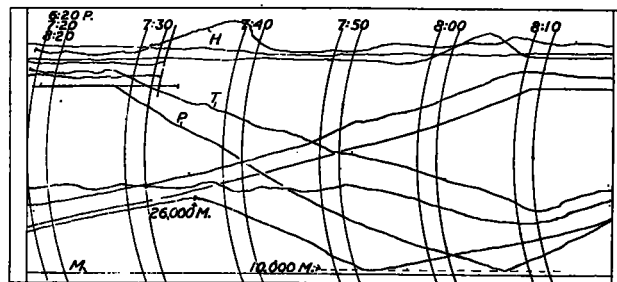
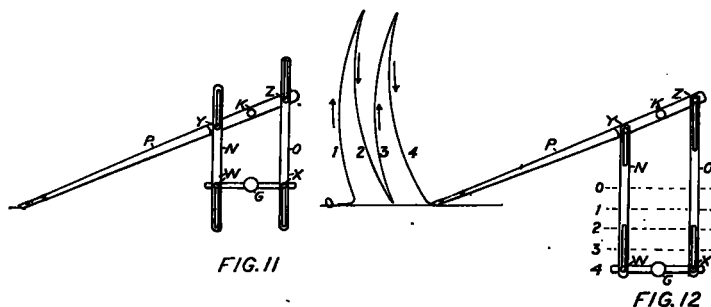
The mechanism shown schematically in figures 7 to 12, inclusive, should meet the very exacting conditions described perhaps more satisfactorily than any hitherto employed. This device was first employed by the writer in a precipitation gauge in which the pen was caused to move four times across the record-sheet. In the present instance of the meteorograph two traverses of the sheet probably will be sufficient.

The pen-arm (P) is heavier at the end bearing the marker, and at sea-level (figure 8), its position is controlled by the slotted link (O). At any desired height, for example, 10,000 meters, as in figure 9, the marker has reached the lower limit of the scale and is prevented from going further in this direction by the other slotted link, (N). If further reduction of pressure occurs, the arm is raised by the link (N), the screw-pin on the other side of the axis sliding downward in the slotted end of the link (O). The movement in this reverse direction can continue until the limits of both slotted links have been reached, which, in the instance of the meteorograph under consideration, should be set at the zero of the pressure-scale.

An important feature of this mechanism is the variable scale. The links (O) and (N) may be so placed with reference to the axis or pivot (K) that the upward movement of the marker has twice the value of the lower (or downward), in order that the small changes of pressure at heights above 10,000 meters may be read with greater accuracy than would be possible with a uniform scale. With a sufficiently powerful pressure-element the upper portion of the record easily could be given three or more times the value of the lower for the same change of pressure.

Mechanism for four-part record.—The mechanism employed to obtain four traverses of the record-sheet, while perhaps more useful in precipitation gauges or other totalizing instruments, may be of some value in aerological apparatus. As shown in figures 11 and 12, both ends of the links (N) and (O) are slotted and the end of the pen-arm to the right of the axis is heavier than the end carrying the pen. Assuming that the device is applied to a weighing gauge whose receiver is displaced down-

ward as rain or snow falls, this movement may be indicated by successive positions (1), (2), (3), and (4) of the bar (G). When position (1) is reached, the pivot screw (Y) is at the top of its slot, and if further movement occurs must carry the weight of the link (N). The pen end of the recording style is now the heavier, and as movement progresses toward position (2) the pen returns to its starting point. At position (2) the pivot screw (Z) is at the top of its slot and carries the weight of the link (O), restoring the condition obtaining at the beginning. Movement toward position (3) carries the pen upward until the pivot screws (Y) and (W) are at the top and bottom, respectively, of their slots. During movement toward position (4) the pen is drawn downward on its fourth excursion until zero (or the limit of the lower slot in link (O) is reached), although safety to the mechanism might require the use of a suitable device for checking the movement before zero is attained.



SEP. 1920

FIG. 13

By the use of this mechanism it is possible to quadruple the capacity or the scale values of recording gauges, etc., without costly increase of dimensions of clock-drums, record sheets, etc., or in the instance of seasonal or long-period apparatus to facilitate obtaining records at isolated stations where observers can not be secured.

Humidity.—The humidity-element (H), figures 1 and 2, consists of six or eight strands, each composed of three fine hairs. Tension is maintained by a flat spring (I), the outer end of which is connected with the recording style. By this method of construction the highest degree of sensitiveness is attained and the hairs are protected against direct sunlight.

Support for recording styles.—The pivots of the recording styles are supported by a one-piece aluminium casting (D). All three axes are at the same height and there is but one time-arc for all. The positions of the pivots, screws, etc., are indicated on the pattern, and if smooth castings are obtained the only machining necessary is boring for pivots and screws and smoothing the under side which rests on the base plate. To provide for the double traverse of the pressure-marker, its pivot is placed exactly 3 mm. (or one minute of time) behind the others,

and the recording points are of different lengths so that one may pass over or under the others.

Case and base.—The case (A) is of hard sheet aluminium, 35 gauge (or 0.2 mm.) thick, the cover is secured by a lock seam instead of rivets, and the sides are stiffened by two or more deep "heads" or ribs. The bottom edge is double and is secured to the base (B) by means of machine screws at intervals of about 5 cm. Access to the mechanisms is afforded by a sliding door (shown in the photograph), and the clock-drum is removed or replaced through an opening in the top of the case, which at other times is closed by the cap (U), figure 1. This cap and the sliding door can be secured by screws, so that the instrument is not likely to be opened and injured by a curious finder.

The base (B) is of hard sheet aluminium, 26 gauge (0.5 mm.) thick, and as shown in figure 2, is made as rigid as possible by bending up the edge continuously on all sides.

Considered separately, the case and base are fragile and not so rigid as similar parts of other instruments; but, when put together, they resist, as a solid block, all ordinary stresses, and since as stated, the recording mechanisms are carried in a separate, rigid casting, accidents serious enough to deform both case and base in most instances do not injure these more delicate parts.

Parachute.—For this apparatus, whose weight, including accessories, is but one-third that of the equipment employed by Teisserenc de Bort (the next lightest), a parachute having one-third the surface of the one used by de Bort will be sufficient. The parachute may be dispensed with, but in this event, two pieces of bright-colored silk should be attached to the apparatus to retard the descent and to attract the attention of a possible finder. If a parachute is employed the gores should be of different bright colors to facilitate discovery. Methods of making parachutes are well known and do not require description here.

Record sheets.—These are made of hard sheet aluminium about 44 gauge (0.03 mm.) thick (almost as thin as foil), and can best be secured to the record drum by means of the lockjoint used in the first experiments at St. Louis.

Records.—In figure 13 is shown schematically the kind of record made by the new instrument. The traces may be read by means of a transparent scale, but, as indicated, it will probably be best to rule a pair of time-arcs for each interval of 10 minutes and measure all intermediate readings from these lines. The usual fixed marker, (M), traces a base-line from which the positions of the other markers at different temperatures, pressures, and humidities can be determined, and which serves to detect irregularities in the movement of the clock drum.

Dimensions and weight.—The external length of the instrument is 210 mm., the height 90 mm., and the greatest width 85 mm. The clock-drum is 80 mm. in length, 57 mm. in diameter, and the time-scale is 3 mm. a minute. The weight of the clock and drum, including a cover for the clock is 65 grams.

METEOROLOGICAL APPARATUS FOR USE WITH THE GODDARD ROCKET.

The Goddard exploring rocket has been suggested as a means for obtaining meteorological data at heights greatly exceeding those accessible by balloons. Propelled by charges of explosive fired at frequent intervals, its velocity is very high, and the ascent to and the descent from a height of 100 kilometers requires only about 10

minutes. Under such circumstances the best methods of measurement now available are not likely to yield data of more than approximate value at first. The vacuum existing above 50 kilometers is not easily attained or measured by an ordinary air pump, and it may be necessary to employ several independent methods to ascertain the conditions at any desired point during either ascent or descent; for, during the descent, a parachute will be of little use until the troposphere is reached. The following methods have been suggested for obtaining heights:

(1) In the daytime, trigonometric measures of smoke-clouds produced at definite intervals by chemicals placed among the charges of explosive. At night charges of magnesium are to be substituted for the smoke-producing materials. (Humphreys.)

(2) The measurement of vacua in a series of exhausted vessels arranged to be opened and resealed at predetermined points. (Humphreys.)

(3) The use of recording apparatus.

The first method is probably the most accurate and the third the simplest, if the scales can be made wide enough to indicate the very small changes occurring in the stratosphere. The development of recording apparatus adapted to these conditions is well worth while, for

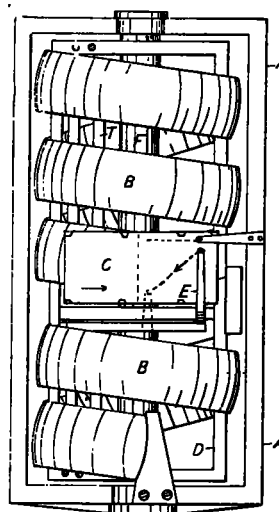


FIG. 14

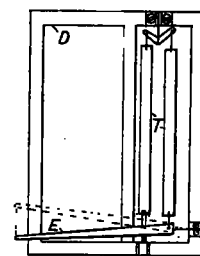


FIG. 15

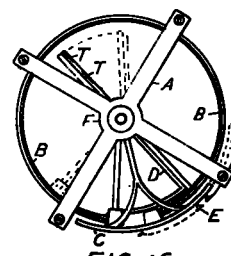


FIG. 16

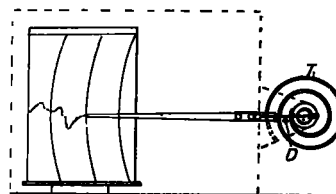


FIG. 17

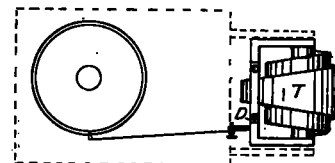


FIG. 18

SPF, 1920

there are projects other than the present one of the exploring rocket in which a simple instrument without clock will be useful. The conditions under which such an instrument must function are very trying. The shock of the frequent explosions and the strain caused by the high velocity are very likely to destroy an instrument with delicate mobiles, consequently time-clocks and mechanisms ordinarily employed in measuring temperature and

pressure need not be considered at present. The range of movement required and freedom from vibration must be secured by the use of strong elements well supported.

The apparatus described herein is suggested as a basis for further experimental study. It has not been constructed, but the principle of Mr. Dines's successful engraving instrument has been followed, and essential parts already have been used to a limited extent in instruments produced by Richard and other manufacturers. Referring to figures 14, 15 and 16, the pressure-element (B) is composed of two helical Bourdon tubes secured in a light frame (A), so that their free ends move in opposite directions when there is a change of pressure. A single tube could be used, but the double-tube element is preferred for the reason that thereby may be secured greater compactness and rigidity. One tube carries the record-plate (C), and the other the temperature-element. The latter consists of two or more strips of very thin bronze (T, T), connected by spring hinges and

mounted in a light invar frame (D), in such manner that changes of length corresponding to changes of temperature are engraved upon the record-plate by the style (E). The strips (T, T) are insulated from their support.

The inner ends or edges of the plate-carrier (C) and the frame (D), are secured, under tension, to spring hinges in the center of the tube (F), and therefore restrict the motions of the pressure tubes to an arc whose axis is the center of the tube (F). By this means longitudinal movements of the pressure tubes are prevented and there are no pivots with the variable friction inevitable when Bourdon tubes of this kind are mounted in the usual way. Another application of this device, in the construction of a simple thermograph without pivots, is shown in figures 17 and 18. Here, circular motion about the center of the coiled element (T), is obtained by securing to its free end the frame (D). Adjustment for range is accomplished by changing the position of (D) as shown by the dotted lines.

A GENERAL THEORY OF HALOS.

By CHARLES S. HASTINGS.

[Yale University, May, 1920.]

SYNOPSIS.

The general theory of halos developed in this paper rests on the assumptions that two kinds of simple ice-crystals—elongated hexagonal rods and hexagonal plates—are occasionally present in a tolerably transparent atmosphere; moreover, that these crystals subsiding in quiescent air would necessarily fall into four groups.

The first portion of the paper establishes the validity of the assumptions by reference to well-recorded observations.

The second portion is devoted to a development of the consequences from the presence of each of these groups for various altitudes of the sun. It is there shown that all the authenticated features of complex halos are naturally explained (excepting certain rare multiple concentric circles) as inevitable consequences of the hypotheses. In addition, this portion gives a new means of classifying the various phenomena, showing unsuspected relationships as well as essential diversity in certain other cases where common origin was formerly assumed.

I.

During the 72 years which have elapsed since Bravais published his celebrated and comprehensive work on halos many observations have been accumulated—some even by means of photography—and much has been written in the effort to improve questionable points in the theory presented by that admirable writer. As regards the efforts of the theorists it does not seem unfair to say that they have been quite futile; at least, no solution of a difficulty left by Bravais, as far as known to me, has ever commanded general acceptance. The elaborate mathematical discussions by Pernter of the tangent arcs to the 46° circle and of the, so called, arcs of Lowitz, perfectly illustrate the rather sweeping statement: Each of these is a logical conclusion from premises which no instructed meteorologist can possibly accept.

Before advancing any new views regarding the highly complex phenomena involved it will be well to summarize what was known when Bravais finished his work. The number of features which he considered and attempted to account for was about twenty. Of them we may ignore one or two as not being sufficiently authenticated, but we must add two which are of unquestionable authenticity; thus the total number remains nearly the same. Unfortunately, a small minority only of these were satisfactorily explained. We may catalogue these

here and escape an undue lengthening of this paper by unnecessary repetition.

(1) The ordinary circle about the sun of 22° radius, attributed by Mariotte to the action of ice crystals suspended in the air and having faces inclined at 60° , the directions of their crystallographic axes being entirely fortuitous. This explanation of the commonest of all halos is thoroughly satisfactory and universally accepted.

(2) The 22° -parhelia, often called sun-dogs, are prismatic images of the sun right and left of it and at the same altitude. With a low sun they are at the angular distance named, but at a higher altitude the angular separation increases. They are not seen higher than 50° . At high latitudes they are more frequently noted than any other feature and the explanation—also first advanced by Mariotte—as due to hexagonal ice crystals with persistently vertical axes leaves nothing to be desired.

(3) The parhelic circle—a faint, colorless circle everywhere equally distant from the zenith and passing through the sun. This was attributed by Thomas Young to reflection from the faces of hexagonal prisms falling vertically. Bravais improved this theory by the remark that crystals with their principal axes persistently horizontal would also contribute to this feature. I shall show that probably only such reflection as is total, hence from the interior of the crystals, is generally effective.

(4) Upper and lower tangent arcs to the 22° -circle. These are due to the presence of crystals whose principal axes are horizontal, the lateral faces having any direction in space. As the sun rises to an altitude of about 45° these two arcs unite and form a ring inclosing the 22° -halo and touching it at its highest and lowest points. At very high sun this ring, called the circumscribed halo by Bravais, approaches more and more a true circle. This ring may exist alone. Admirable photographs taken at New Haven, Conn., and at Chester, Pa., of the halo of March 20, 1915, have been published in the MONTHLY WEATHER REVIEW.¹ Bravais gave a very complete analysis of these features with tables which may be used to find the position of any desired point

¹ May, 1915, 43: 213-216 and October, 1915, 43: 498-499.